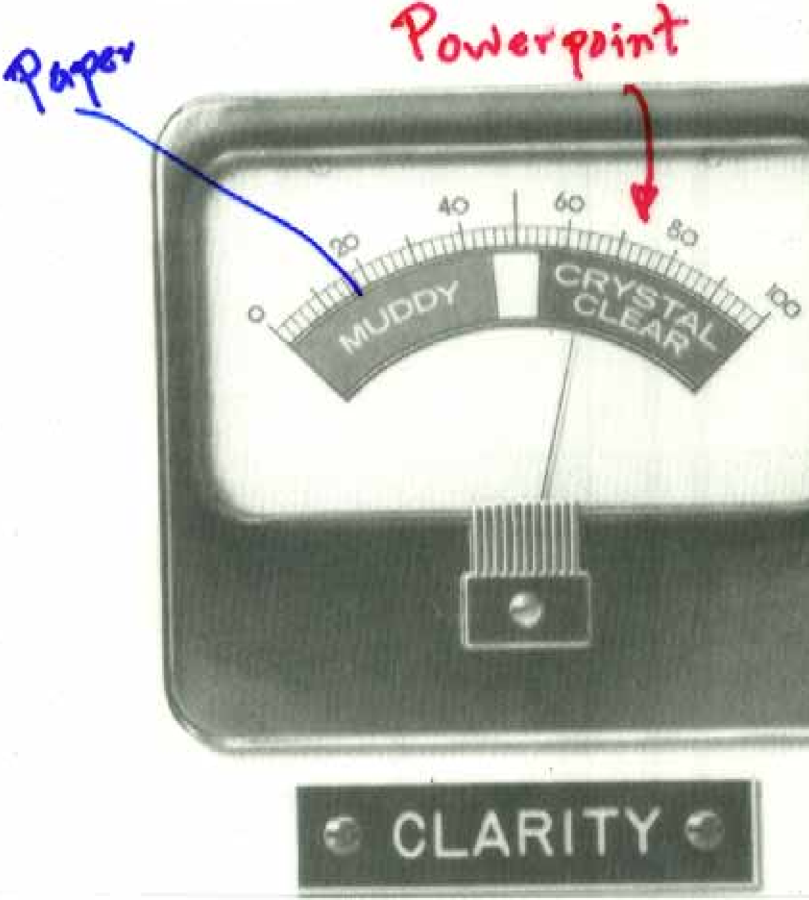
ECE 562

Week 7 Lecture 2

Fall 2008

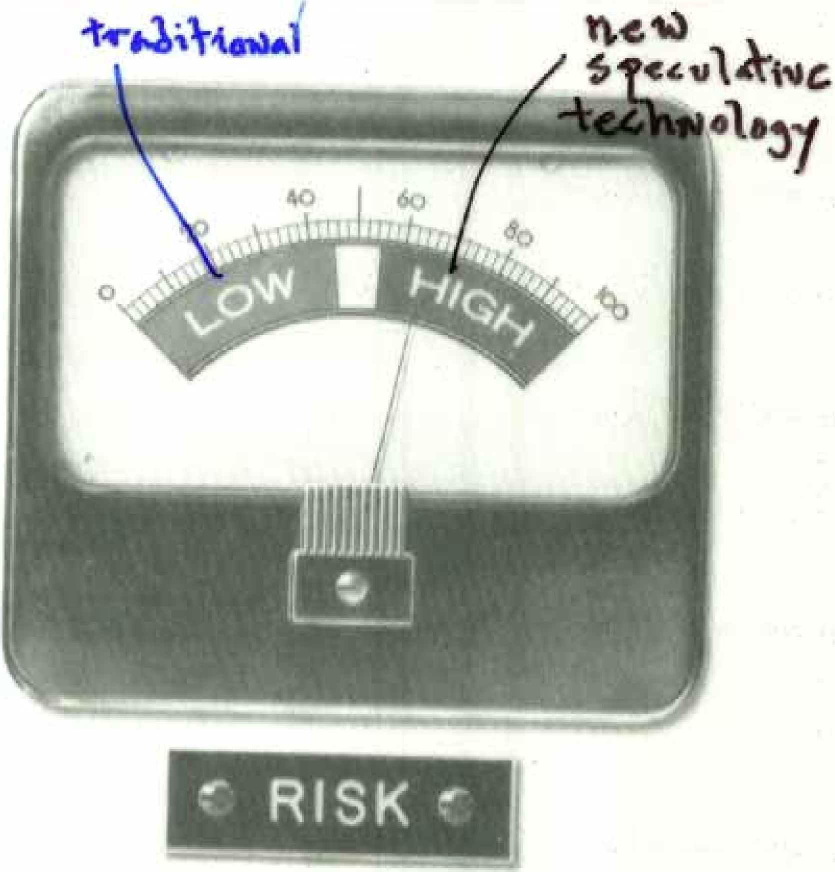
Week 7 Lecture 2
Summary

- Section notes
  - Slides 3-6 – In-class talk criteria
  - Slides 7-25 – Insulated Gate Bipolar Transistors (IGBTs)
  - Slides 26-28 – IGBT applications
  - Slide 29-44 IGBT switch characteristics
  - Slides 45-46 –Homework problem 4.7
  - Slides 47-52 – Switching efficiencies
  - Slides 53-57 – Varistors



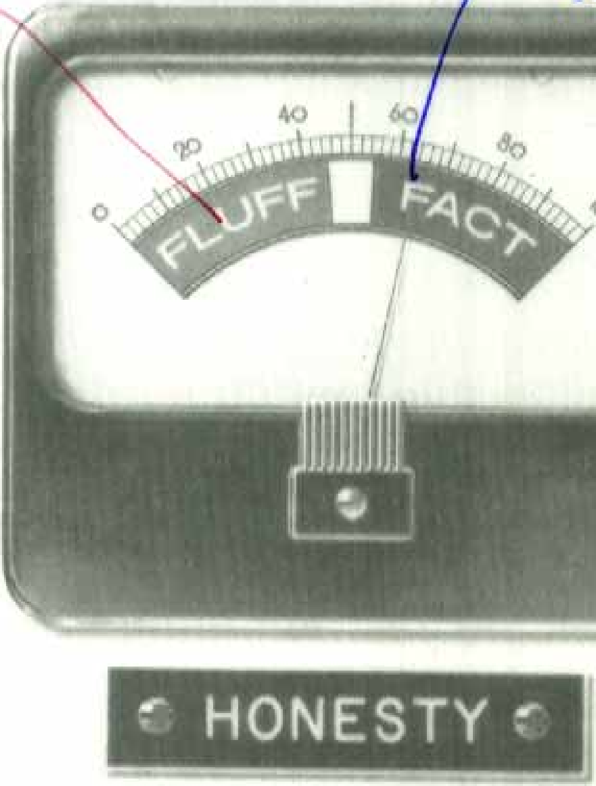
Paper

Powerpoint



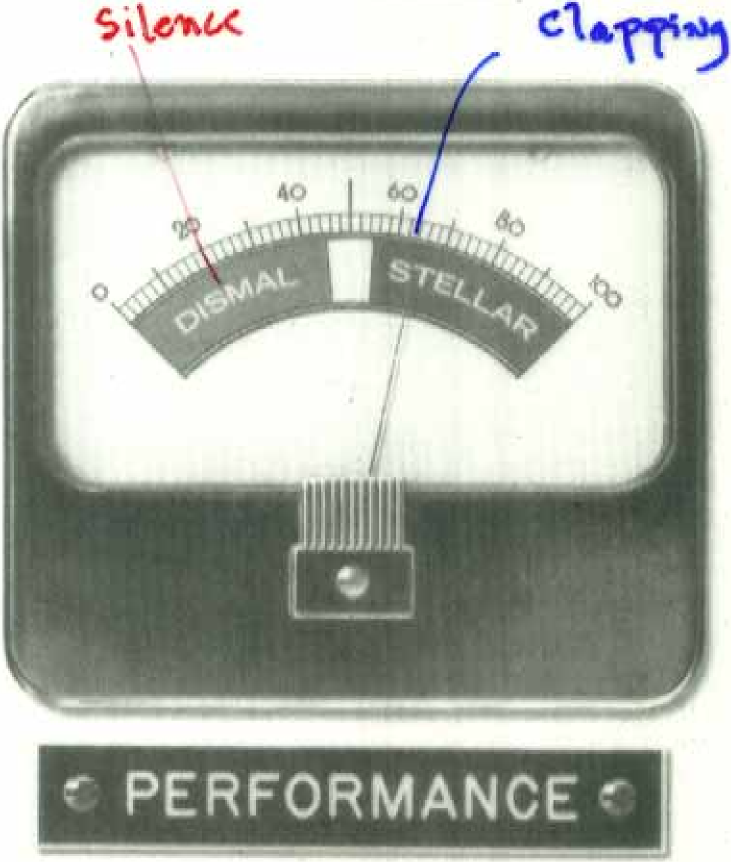
traditional

new speculative technology



Know it when you encounter it

truth tested


Silence
Clapping
0
20
40
60
80
100
DISMAL
STELLAR
PERFORMANCE

Summary of chapter 4

1. How an SPST ideal switch can be realized using semiconductor devices depends on the polarity of the voltage which the devices must block in the off-state, and on the polarity of the current which the devices must conduct in the on-state. OK?
2. Single-quadrant SPST switches can be realized using a single transistor or a single diode, depending on the relative polarities of the off-state voltage and on-state current. OK?
3. Two-quadrant SPST switches can be realized using a transistor and diode, connected in series (bidirectional-voltage) or in anti-parallel (bidirectional-current). Several four-quadrant schemes are also listed here. OK?
4. A "synchronous rectifier" is a MOSFET connected to conduct reverse current, with gate drive control as necessary. This device can be used where a diode would otherwise be required. If a MOSFET with sufficiently low R_{on} is used, reduced conduction loss is obtained. OK?

Two

FET: $I_{ON} R_{DS} \le 0.7V$

70A 10mΩ P=49W

BJT I_{ON} V_{CE}

70 0.2

P ≈ 14W

International Rectifier introduces Economical, High Power, 150kHz IGBTs for High Frequency SMPS Applications

EL SEGUNDO, Calif., February 2003 - International Rectifier, IR® (NYSE: IRF), today introduces new WARP2™ 600V 50A, 35A and 20A non-punch through (NPT) IGBTs with improved turn-off characteristics for high current, high frequency switch-mode power supply (SMPS) circuits in telecom and server systems. The new WARP2 NPT IGBTs offer performance and efficiency with a better price-to-performance value than power MOSFETs. The WARP2 IGBTs are co-packaged with HEXFRED® diodes, which enable better performance compared to the integral body diodes in power MOSFETs. The new devices are available in the TO-247 and TO-220 packages.

Part Number	Package	VCES	IC @ 25°C	VCE(on) typ	Co-Pack Diode	Qg
IRGP50B60PD1	TO-247	600	50A	2.0V @33A	15A	205nC
IRGP35B60PD	TO-247	600	35A	1.85V @22A	15A	160nC
IRGP20B60PD	TO-247	600	20A	2.05V @13A	8A	68nC
IRGB20B60PD1	TO-220	600	20A	2.05V @13A	4A	68nC

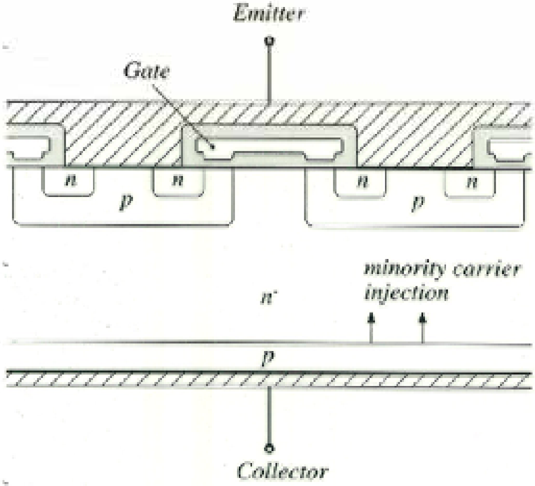
Early IGBT
Similar I, V to FET
Lower ON loss

Big Qg

Availability and Pricing

The new high frequency NPT IGBTs are available immediately. Pricing begins at US $1.00 each for the IRGB20B60PD1 in 10,000-unit quantities.

4.2.4. The Insulated Gate Bipolar Transistor (IGBT)



- A four-layer device
- Similar in construction to MOSFET, except extra *p* region
- On-state: minority carriers are injected into n^- region, leading to conductivity modulation
- compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to ~~1700~~V)

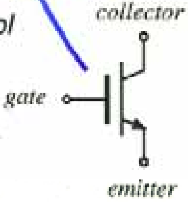
8KV latest IGBT for power grid

Q_G to switch 50-200nC

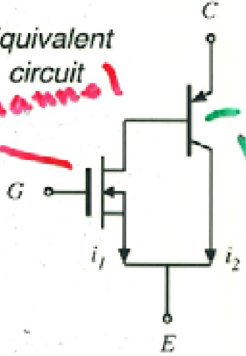
$P_{gate} \sim C V_{Th}^2 f_{sw}$

The IGBT

Symbol



Equivalent circuit



n-channel

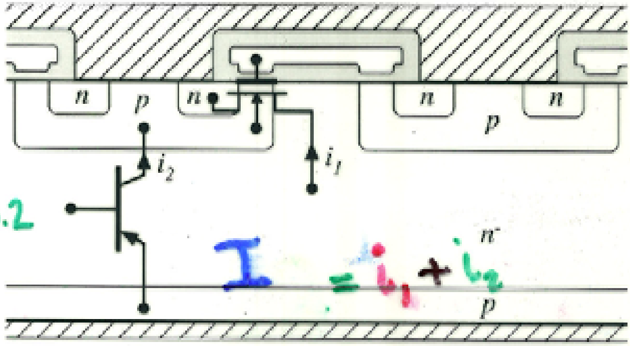
pnp

$V_{sat} \approx 0.2$

low

P_{on} loss

Location of equivalent devices



$I = i_1 + i_2$

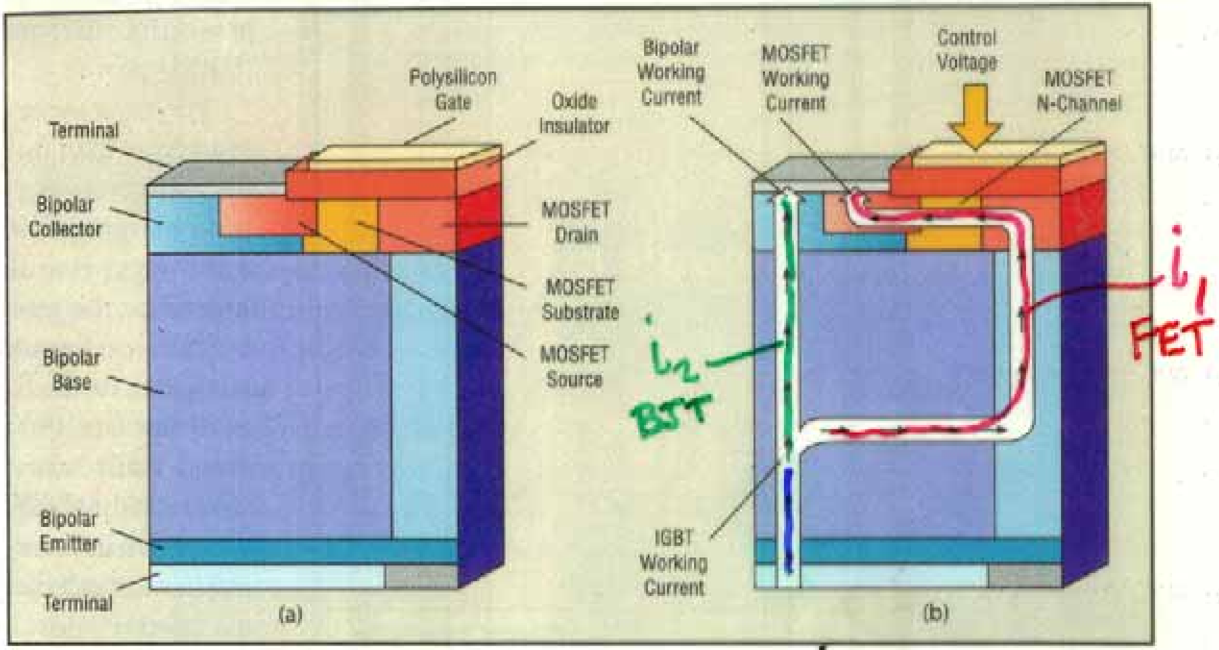


Fig. 2. *IGBT builds on bipolar and MOSFET design. An IGBT employs both bipolar and MOSFET building blocks (a); consequently, IGBT current, shown in IGBT ON state (b), comprises both bipolar and MOSFET currents.*

$$I^T = I(BJT) + I(FET)$$

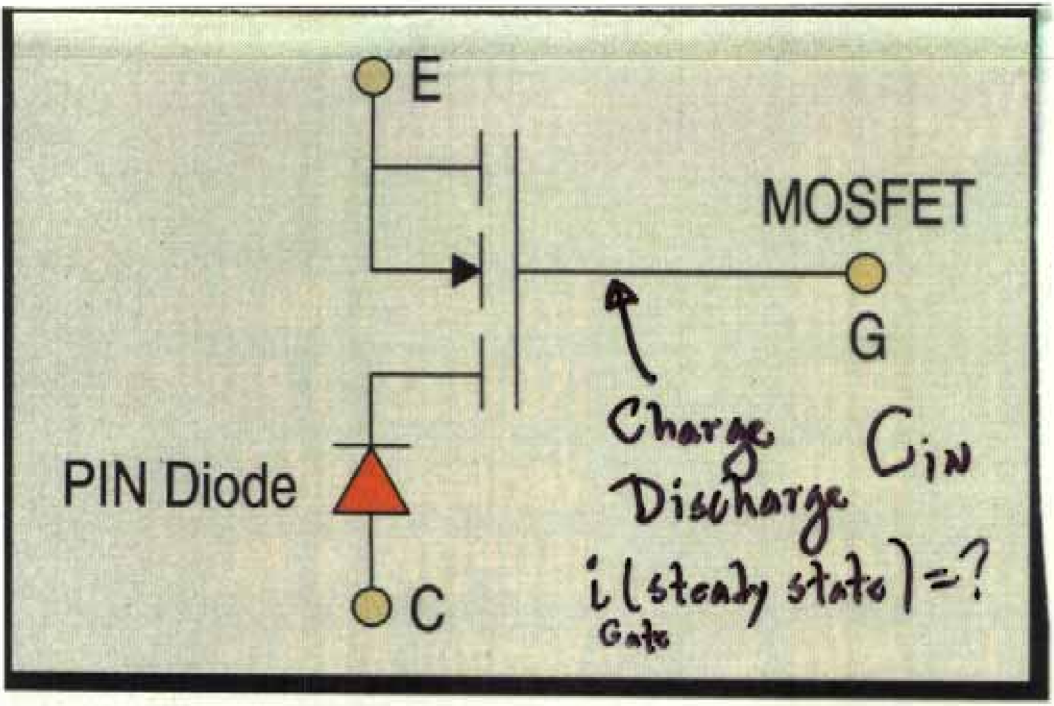
low f_{sw}

White goods Appliance

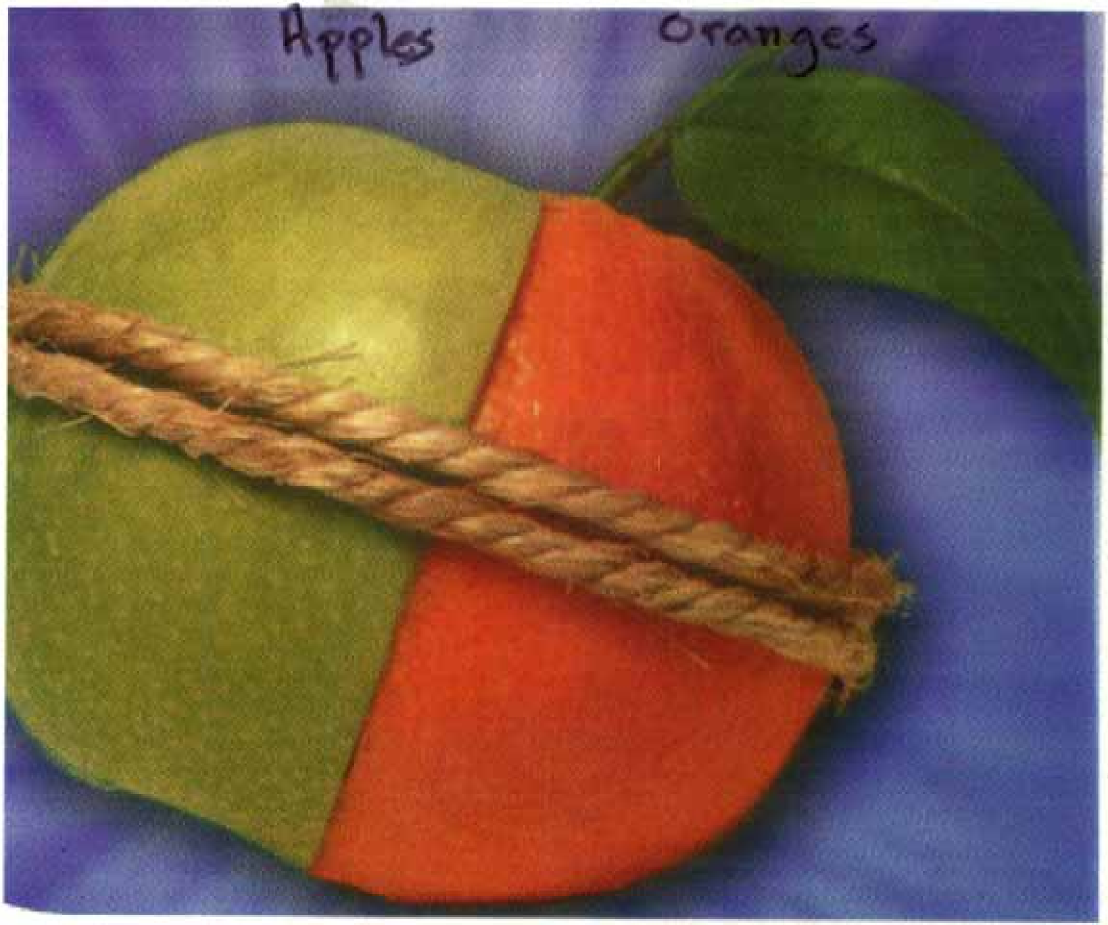
IGBTs Preferred	MOSFETs Preferred	IGBT Applications	MOSFET Applications
High duty cycle	Low duty cycle	Motor control	Switched-mode power supplies
Frequencies of 20 kHz or less	Applications of 200 kHz or more	Uninterruptible power supplies	Battery charging
Small line or load variation	Wide line or load variation	Welding	
High-voltage applications of 1000 V or more	Low-voltage applications of 200 V or less	Low power lighting	
Output power of 5 kW or more	Power outputs of 500 W or less		
Junction temperatures of 100°C or more			

Table. *IGBTs versus MOSFETs.*

High Duty Cycle ON $\Rightarrow$ P_{on} matters



ig. 1. *On-State Model of IGBT.*


Apples
Oranges

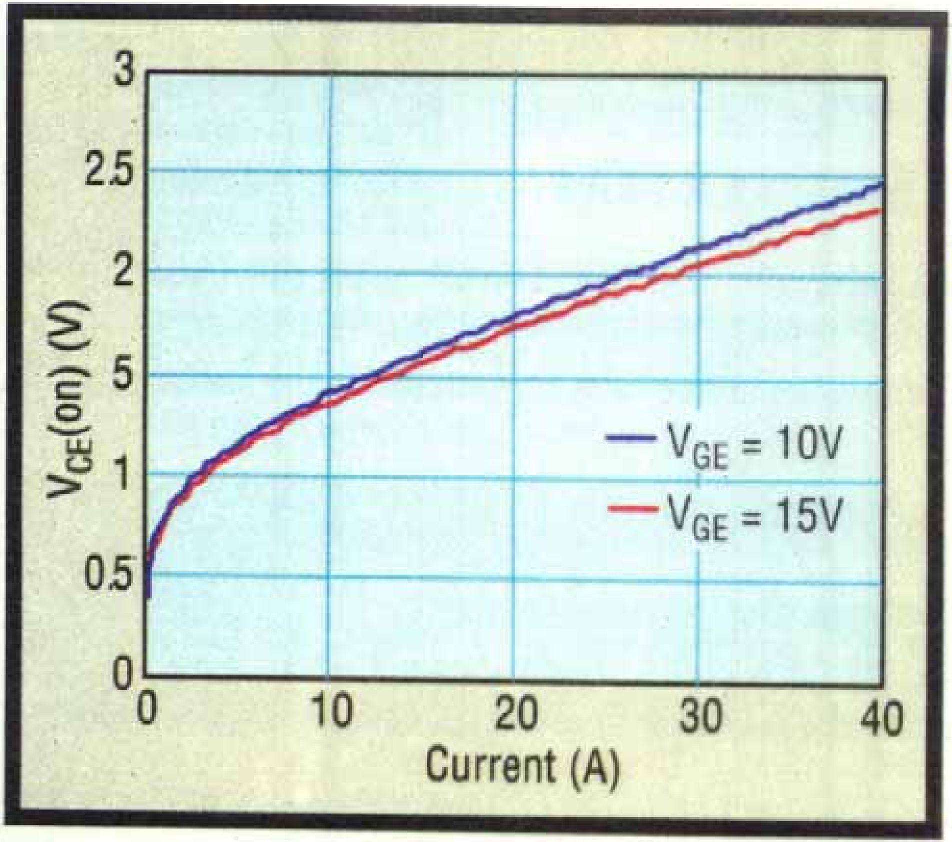


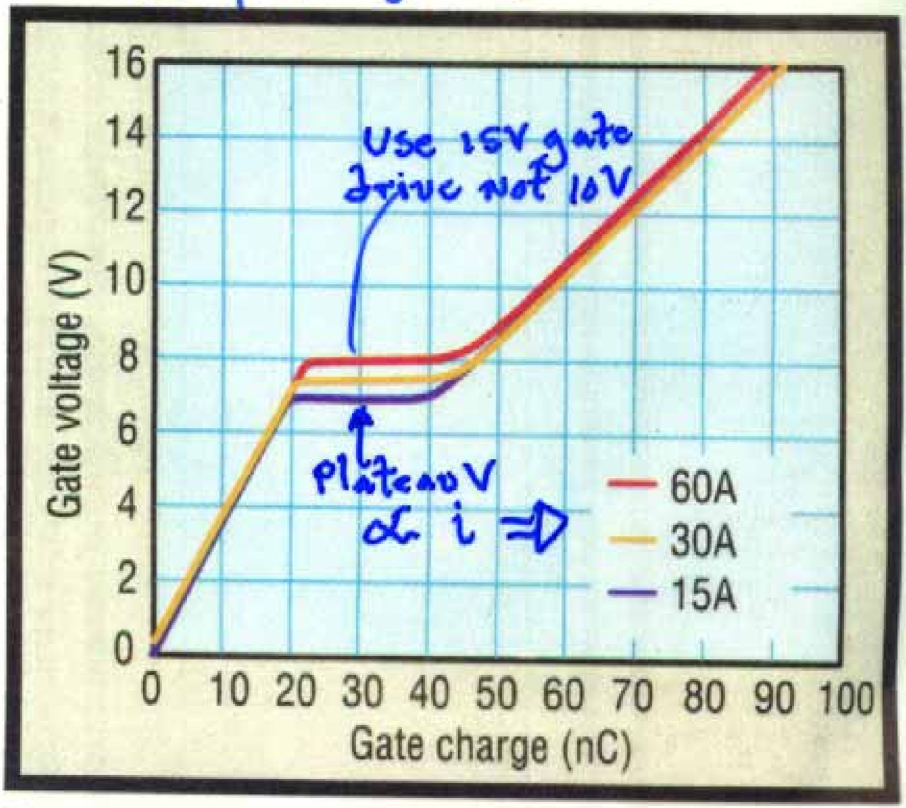
Fig. 4. *APT30GP60B on-state voltage vs. current*

Output

V_{across}

$I_{through}$

Input Vg - Qg



Use 15V gate drive not 10V

Plateau V ∝ i ⇒

Fig. 5. *Gate charge for APT30GP60B at 15A, 30A*

Best Feature Adv Power Tech Spec Sheet

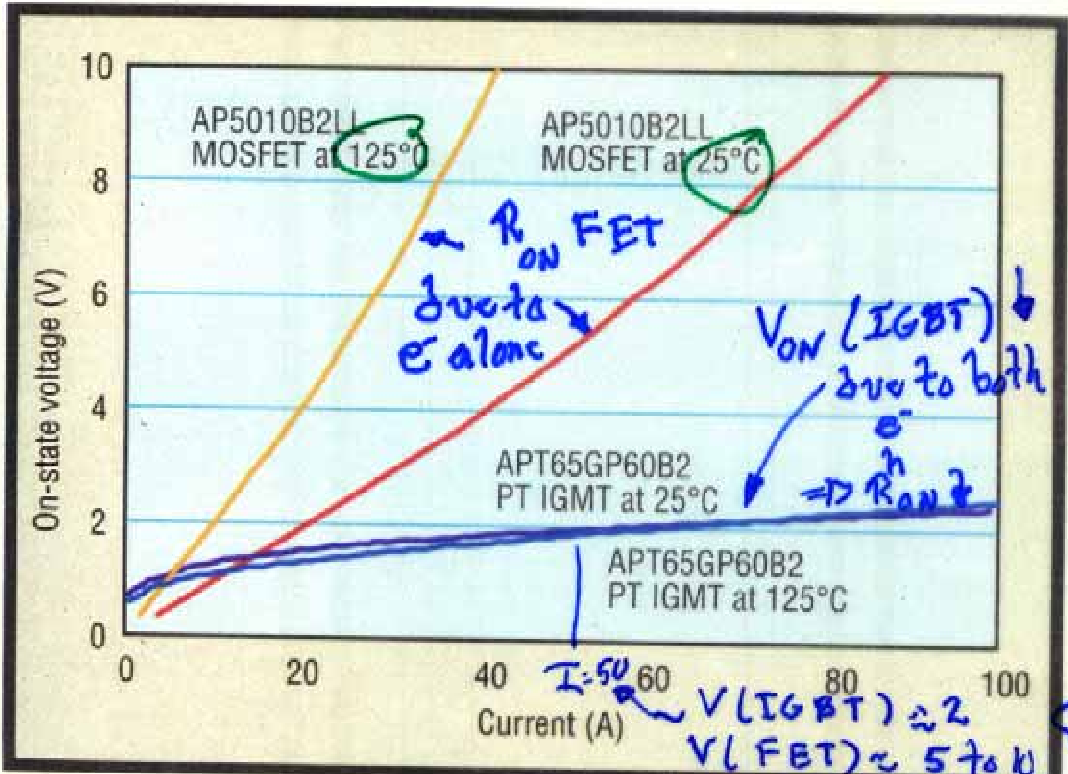


Fig. 1. *On-state voltage vs. current for same size power MOS7® MOSFET and IGBT, 15V gate bias.*

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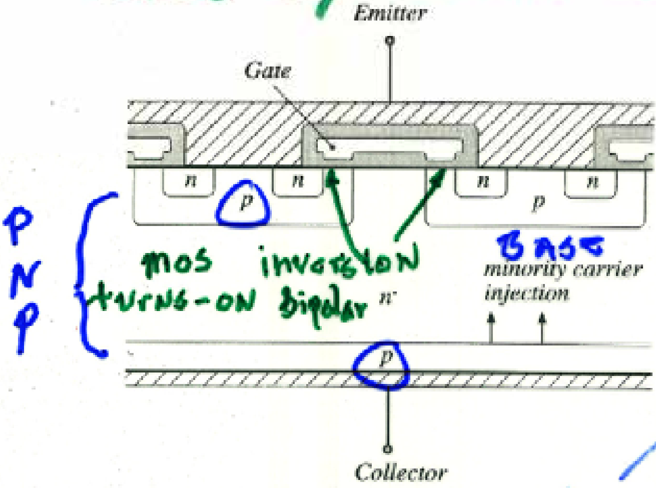
Fig 4.34 Pg 86

4.2.4. The Insulated Gate Bipolar Transistor (IGBT)

NEW Kid in town Wide use

Used by "Motor Heads" ⇒ Lower cost



- A four-layer device

Low f

- Similar in construction to MOSFET, except extra *p* region

High I

- On-state: minority carriers are injected into n^- region, leading to conductivity modulation

uses bipolar Vce

- compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)

3600 V

f up to 100kHz

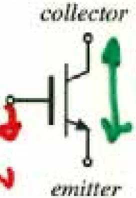
typically 30 kHz

Figs 4.38
4.39 Pg 287

The IGBT

early IGBT } Now in place is 8000 V IGBT for "Power system DVC"

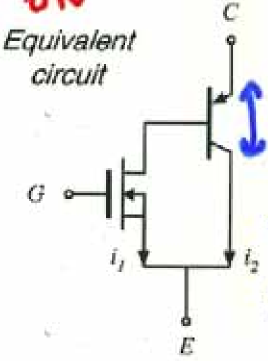
Symbol



[1700 V – 2600 V }

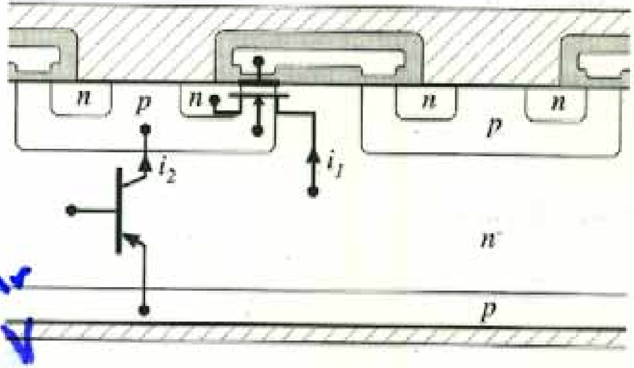
· No S.S.
v_{ON} needed to keep sw ON

Equivalent circuit

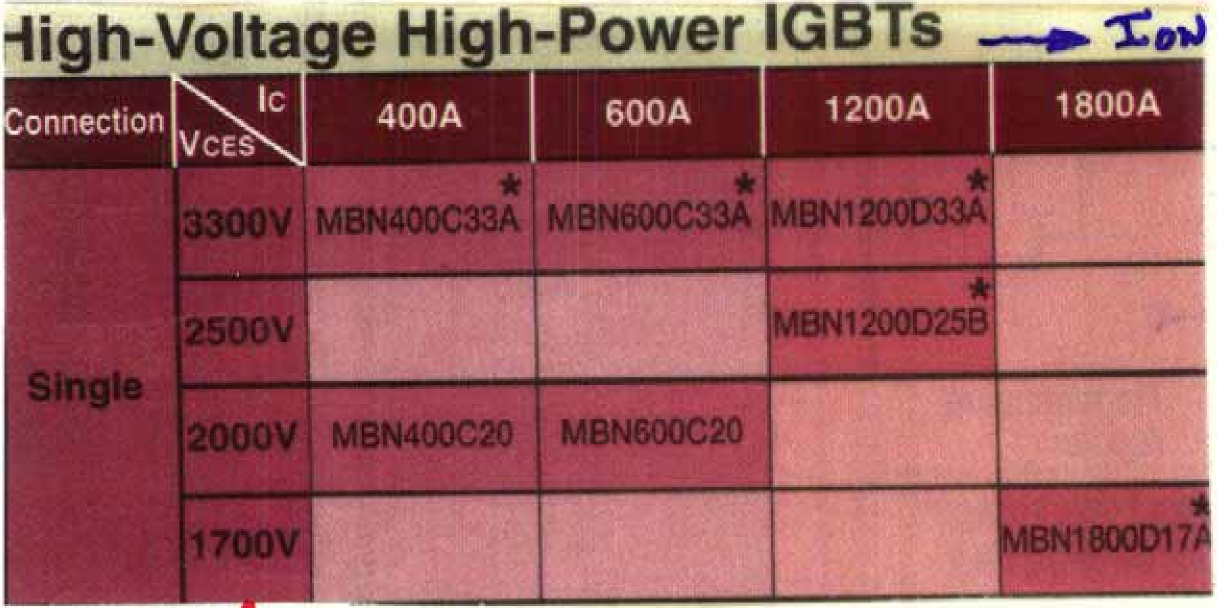


low V_{ON} of bipolar ≈1.3 V

Location of equivalent devices



High-Voltage High-Power IGBTs → I_{on}



Connection	Ic / VCES	400A	600A	1200A	1800A
Single	3300V	MBN400C33A*	MBN600C33A*	MBN1200D33A*	
	2500V			MBN1200D25B*	
	2000V	MBN400C20	MBN600C20		
	1700V				MBN1800D17A*

↑ V_{off} (max)

$I_{on} V_{off} \approx$ MW switching for several μs

lug nut
for wires

ADVANCED POWER TECHNOLOGY®

APT75GP120J

1200V

POWER MOS 7® IGBT

The POWER MOS 7® IGBT is a new generation of high voltage power IGBTs. Using Punch Through Technology this IGBT is ideal for many high frequency, high voltage switching applications and has been optimized for high frequency switchmode power supplies.

- **Low Conduction Loss**
- **Low Gate Charge**
- **Ultrafast Tail Current shutoff**
- **50 kHz operation @ 800V, 28A**
- **20 kHz operation @ 800V, 44A**
- **RBSOA rated**

{↑ de-rate}

MAXIMUM RATINGS

All Ratings: T_C = 25°C unless otherwise specified.

Symbol	Parameter	APT75GP120J	UNIT
V_{CES}	Collector-Emitter Voltage	1200	Volts
V_{GE}	Gate-Emitter Voltage	±20	
V_{GEM}	Gate-Emitter Voltage Transient	±30	
I_{C1}	Continuous Collector Current @ T_C = 25°C	100	Amps
I_{C2}	Continuous Collector Current @ T_C = 110°C	67	
I_{CM}	Pulsed Collector Current ① @ T_C = 25°C	300	
RBSOA	Reverse Bias Safe Operating Area @ T_J = 150°C	300A @ 960V	
P_D	Total Power Dissipation	543	Watts
T_J, T_{STG}	Operating and Storage Junction Temperature Range	-55 to 150	°C
T_L	Max. Lead Temp. for Soldering: 0.063" from Case for 10 Sec.	300	

STATIC ELECTRICAL CHARACTERISTICS

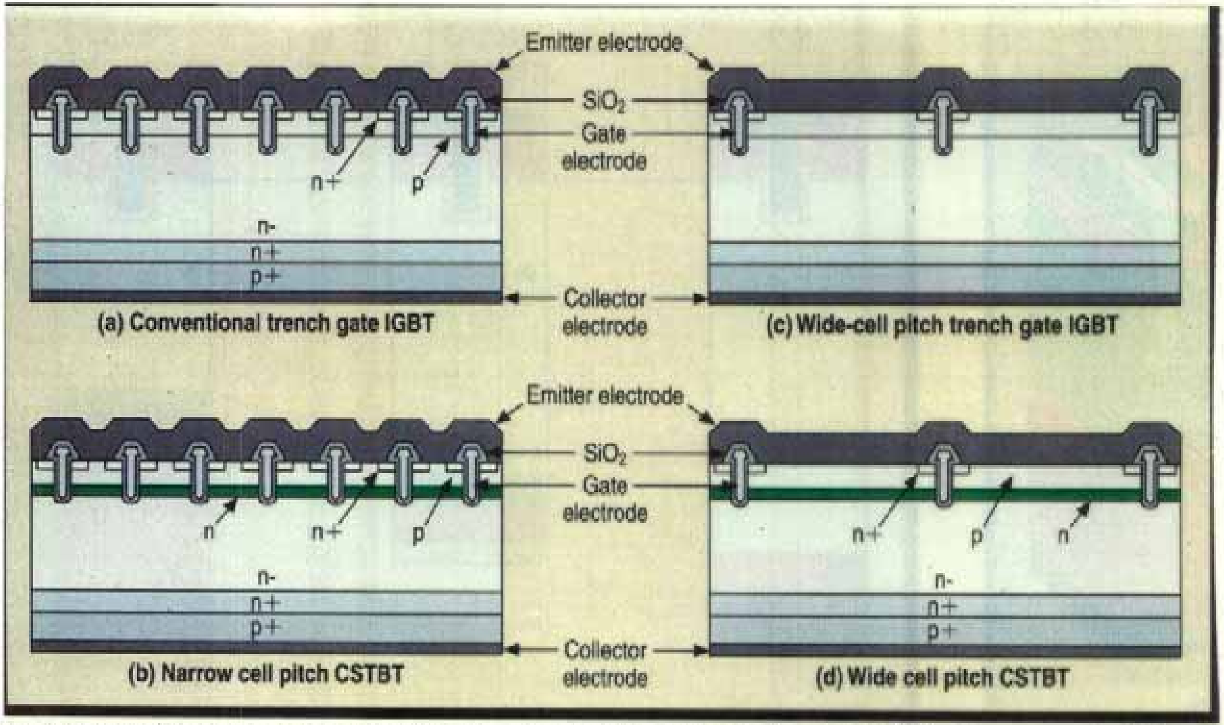
Symbol	Characteristic / Test Conditions	MIN	TYP	MAX	UNIT
BV_{CES}	**Collector-Emitter Breakdown Voltage (V_{GE} = 0V, I_C = 1000µA)**	1200			Volts
$V_{GE(TH)}$	Gate Threshold Voltage (V_{CE} = V_{GE}, I_C = 2.5mA, T_j = 25°C)	3	4.5	6	
$V_{CE(ON)}$	Collector-Emitter On Voltage (V_{GE} = 15V, I_C = 75A, T_j = 25°C)		3.3	3.9	
	Collector-Emitter On Voltage (V_{GE} = 15V, I_C = 75A, T_j = 125°C)		3.0		
I_{CES}	Collector Cut-off Current (V_{CE} = 1200V, V_{GE} = 0V, T_j = 25°C) ②			1000	µA
	Collector Cut-off Current (V_{CE} = 1200V, V_{GE} = 0V, T_j = 125°C) ②			5000	
I_{GES}	Gate-Emitter Leakage Current (V_{GE} = ±20V)			±100	nA

CAUTION: These Devices are Sensitive to Electrostatic Discharge. Proper Handling Procedures Should Be Followed.

APT Website - http://www.advancedpower.com

Table 1. Measured IGBT Parameters.

Test Equipment	DTS_2012T IGBT TESTER
IGBT	BSM75GB120DN2(SIEMENS)
Breakdown voltage (V_B)(V)	1237
Threshold voltage (V_{TH})(V)	5. 517
Oxide thickness (t_{OX})(nm)	85
On_state voltage (V)	3. 165(I_A = 75A, V_g = 12 V)
Turn_on loss (mj)	16. 16
Turn_off loss (mj)	7. 58
A (cm^2)	1. 198 × 1. 198



(a) Conventional trench gate IGBT

(c) Wide-cell pitch trench gate IGBT

(b) Narrow cell pitch CSTBT

(d) Wide cell pitch CSTBT

ig. 5. *IGBT chip structure comparison: a. Conventional trench gate IGBT; b. Narrow cell pitch STBT; c. Wide cell pitch trench gate IGBT; d. Wide cell pitch CSTBT.*

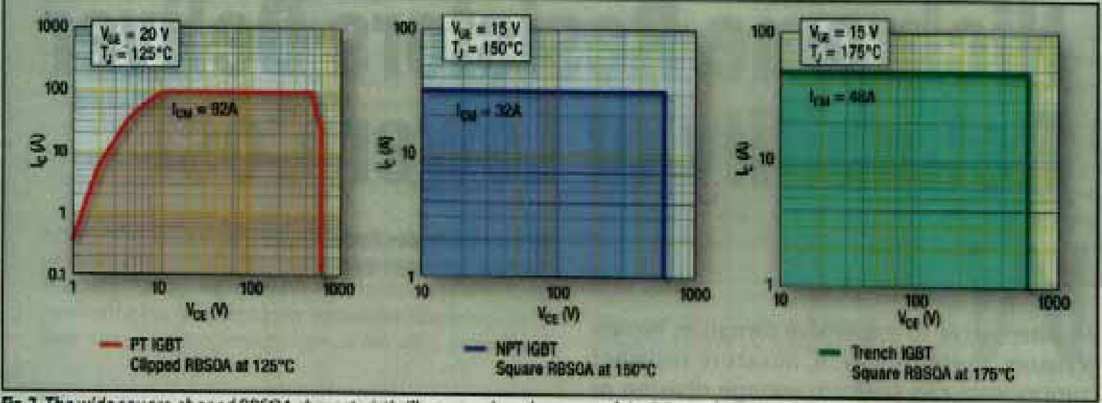


Fig.7. The wide square-shaped RBSOA characteristic illustrates the robustness of the D5 trench IGBT.

Conclusions: IGBT

- Becoming the device of choice in 500-1700V applications, at power levels of 1-1000kW
- Positive temperature coefficient at high current —easy to parallel and construct modules
- Forward voltage drop: diode in series with on-resistance. 2-4V typical
- Easy to drive —similar to MOSFET
- Slower than MOSFET, but faster than Darlington, GTO, SCR
- Typical switching frequencies: 3-30kHz
- IGBT technology is rapidly advancing —next generation: 2500V

Wide use in Motors → low cost sw

V_{ON}

! 6000 !

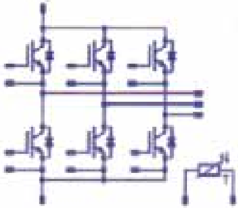
? 10kV 12kV

power system

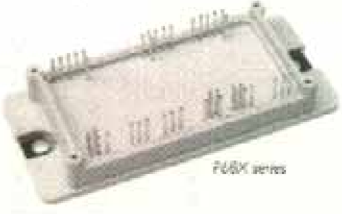
Joe

High Power Sixpacks for Motor Drives

*flow*PACK 2 3rd gen up to 150A at 1200V



- IGBT4 technology for low saturation losses and improved EMC behavior
- Low inductance layout and compact design
- High power *flow* 2 housing



F6BX series

Characteristics of several commercial devices

Part number	*Rated max voltage*	*Rated avg current*	V_F *(typical)*	t_f *(typical)*
Single-chip devices				
HGTG32N60E2	600V	32A	2.4V	0.62μs
HGTG30N120D2	1200V	30A	3.2A	0.58μs
Multiple-chip power modules				
CM400HA-12E	600V	400A	2.7V	0.3μs
CM300HA-24E	1200V	300A	2.7V	0.3μs

Pg 88

Characteristics of several commercial devices

Part number	Rated max voltage	Rated avg current	V_F (typical)	t_f (typical)
Single-chip devices				
HGTG32N60E2	600V	32A	2.4V	0.62μs
HGTG30N120D2	1200V	30A	3.2A	0.58μs
Multiple-chip power modules				
CM400HA-12E	600V	400A	2.7V	0.3μs
CM300HA-24E	1200V	300A	2.7V	0.3μs

300nS

New 6000V

Von Higher than bipolar

Summary of chapter 4

only Δt for parasitics

$f_{sw} \leq 8MHz$

5. Majority carrier devices, including the MOSFET and Schottky diode, exhibit very fast switching times, controlled essentially by the charging of the device capacitances. However, the forward voltage drops of these devices increases quickly with increasing breakdown voltage.

$V_{on} \downarrow$
$V_{ox} \downarrow$

6. Minority carrier devices, including the BJT, IGBT, and thyristor family, can exhibit high breakdown voltages with relatively low forward voltage drop. However, the switching times of these devices are longer, and are controlled by the times needed to insert or remove stored minority charge.

Best of both
except Δt

7. Energy is lost during switching transitions, due to a variety of mechanisms. The resulting average power loss, or switching loss, is equal to this energy loss multiplied by the switching frequency. Switching loss imposes an upper limit on the switching frequencies of practical converters.

high to low Δt_x

Ultra Basics low to high Δt_y

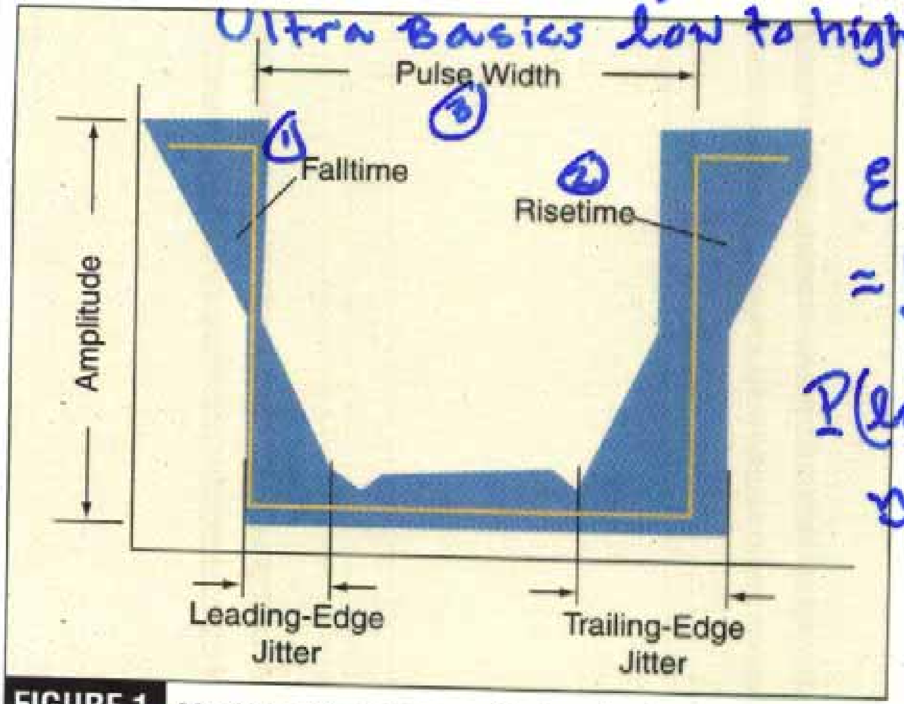


FIGURE 1 Masks define the amplitude, risetime, falltime, and jitter for pulses in telecom networks.

$$\mathcal{E}(\text{switch}) \approx \int_0^{\Delta t} V I \, dt$$

$$P(\text{loss}^{\text{switching}}) \approx \mathcal{E} f_{sw}$$

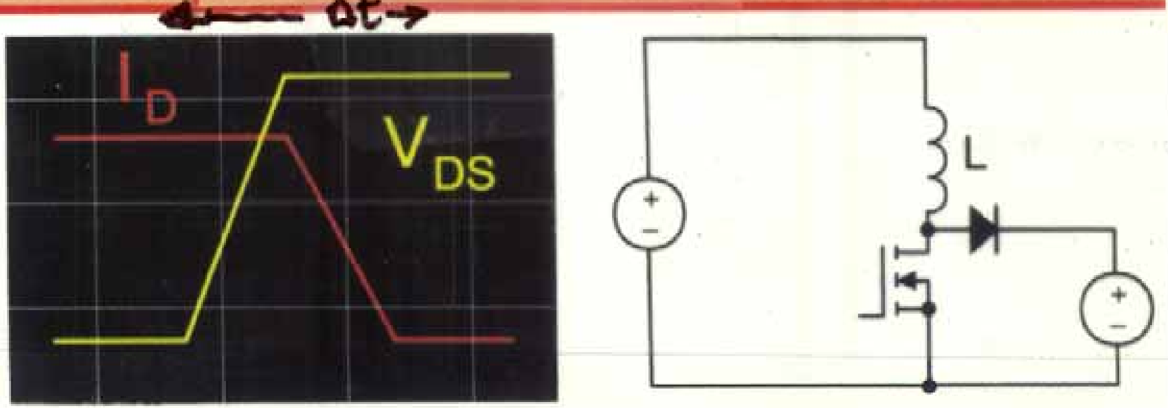
① ON to off transition "L" load

$$P_{loss} = \frac{1}{2} V_{off} I_{ON}$$

$$W_{loss} = P_{loss} * \Delta t$$

Blithly assumes I_L hangs till $V_{DS} \rightarrow$ Max

Fig 3b: Ideal Voltage and Current Waveforms with Inductive Loading

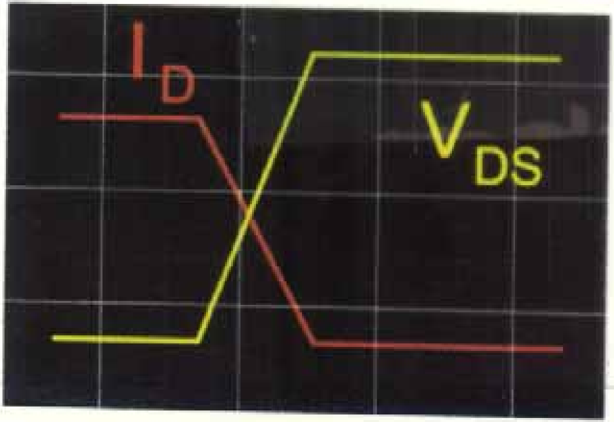


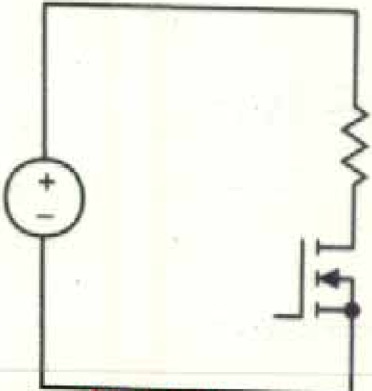
② ON to off Transition R load

$$\left[\frac{1}{6} V_{off} I_{ON}\right] = P_{loss}$$

$$P_{loss} * \Delta t = W_{loss}$$

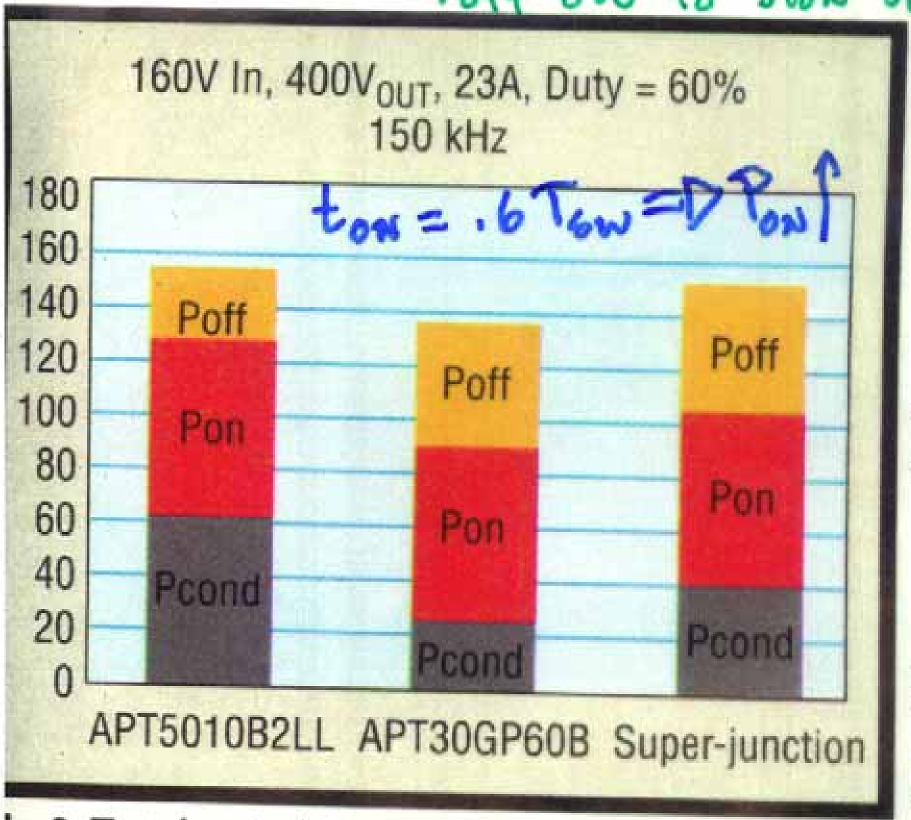
Fig 3a: Ideal Voltage and Current Waveforms with Resistive Loading } other





Ringing

Poff due to slow i(t) decay



$t_{on} = .6\, T_{sw} \Rightarrow P_{on} \uparrow$

ig. 8. *Total switch losses, 23A, 60% duty.*

Total Loss

1. DC losses conduction loss
2. Switch Losses

$$\underline{P}_T = P_{DC} + f_{sw}\, \mathcal{E}_{sw}^T$$

$$\mathcal{E}_{sw}^T =$$

$$\mathcal{E}_{sw}(\text{on-off}) \oplus \mathcal{E}_{sw}(\text{off-on})$$

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Δt(ON-off) (VS) V_{CE}

Tradeoff Required

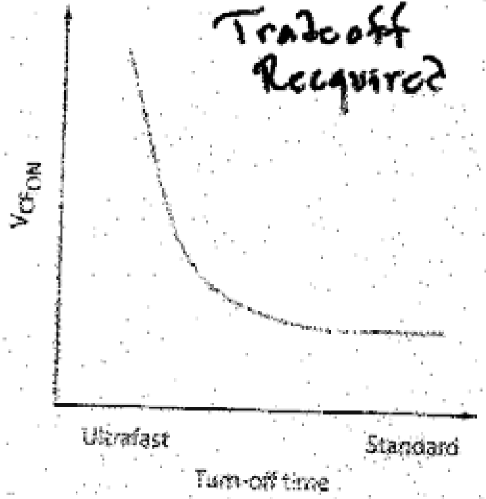


Fig. 1. *Turn-off time for an IGBT is a function of its collector-emitter voltage (V_{CE}). Ultrafast IGBTs have shorter turn-off times than standard-speed IGBTs.*

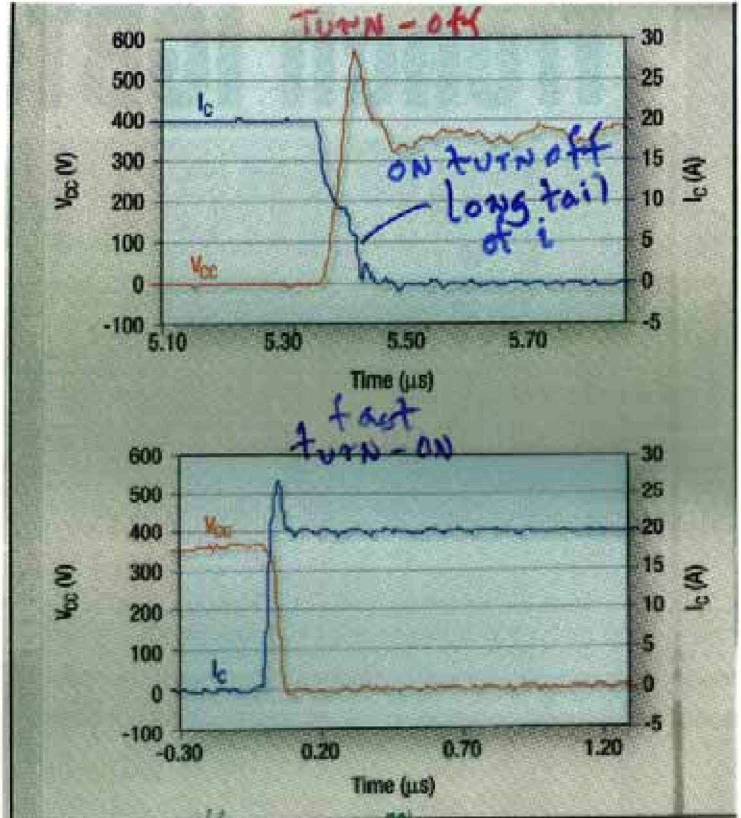


Fig. 3. *Typical turn-~~on~~ off (top) and turn-~~off~~ on (bottom) switching waveforms for DS trench IGBT show the smooth turn-off and reduced current tail for these devices (V_{CC} = 400 V; I_C = 18 A; L = 200 μH; R_G = 22 W; T_{CASE} = 25°C).*

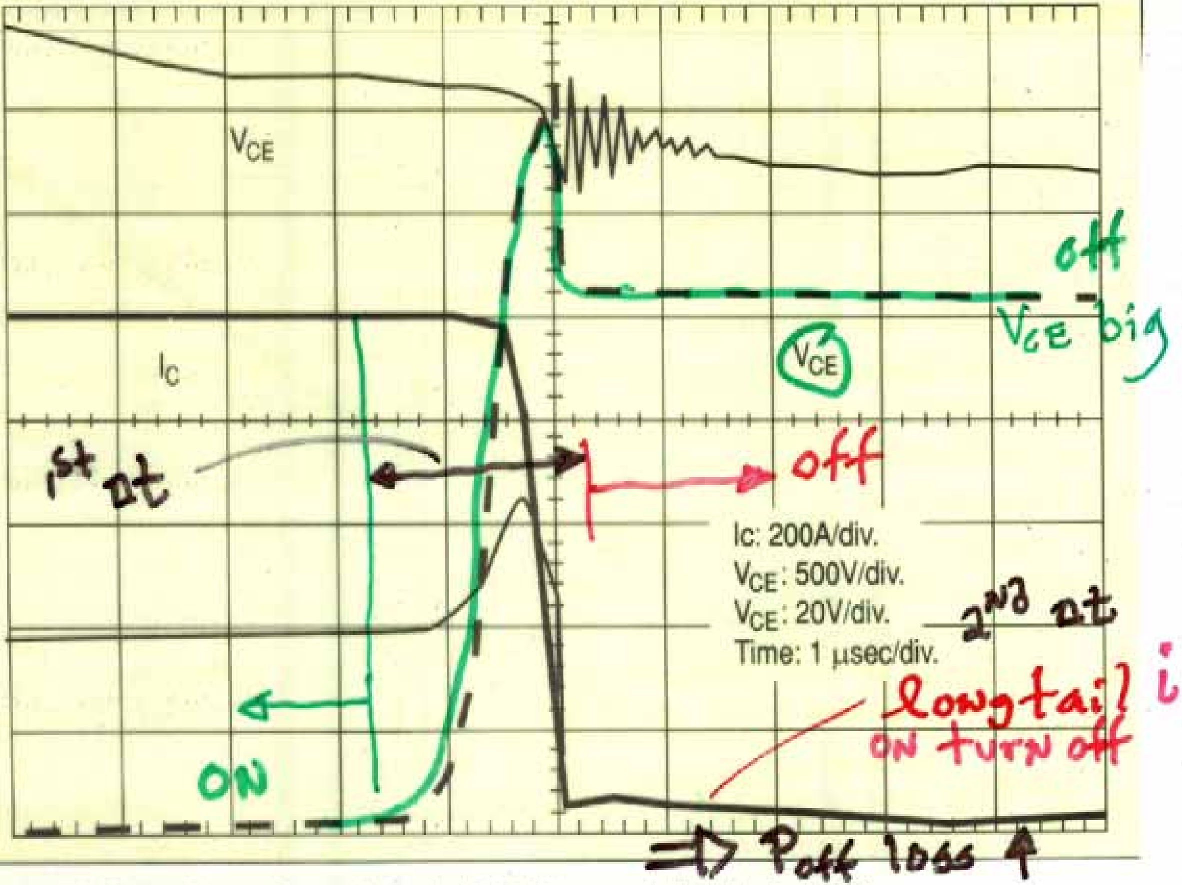
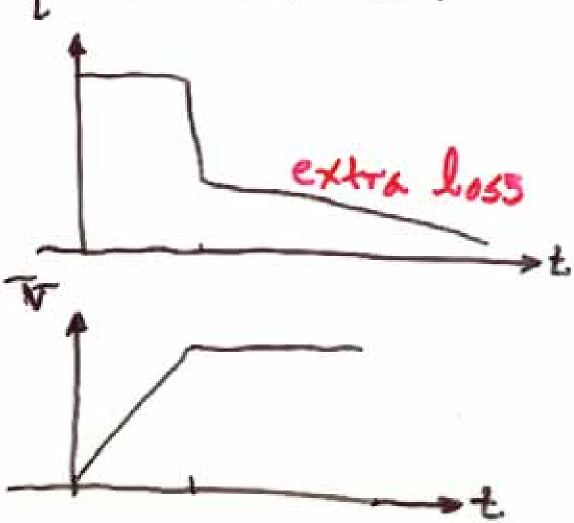


Figure 11. *Turn-off waveforms of trench IGBT. Document Toshiba from* [13]

Longlived $i_{IGBT}(t)$

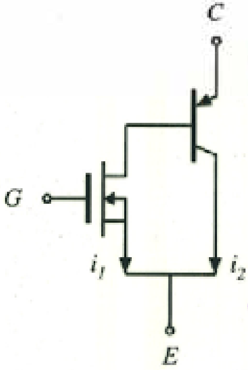
current tail



Worst Featur Pbm 4.7

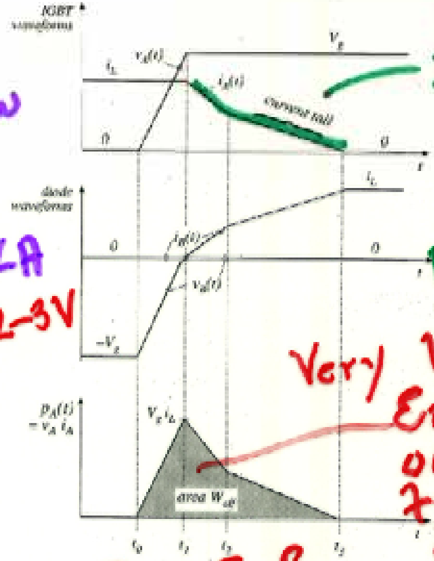
Current tailing in IGBTs

The new Kid has a tail – a long one



Wow I_{on} of 1-2 KA

V_{ON}: 2-3V



sw loss $I_{ON} V_{off} \Delta t$

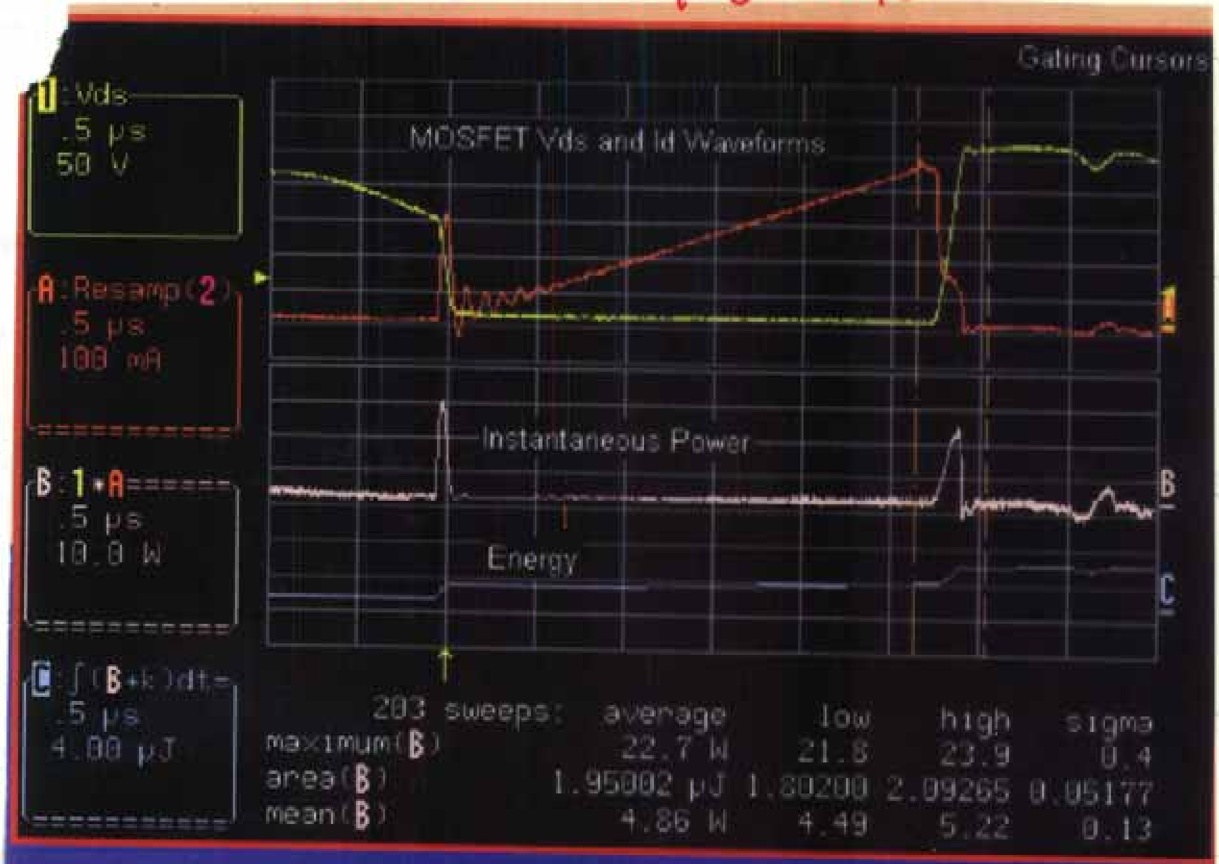
too long

high loss

Very High Energy per on-off transition due to long t_{off}

$P = E_{\substack{ON\\off}} f_{sw}$

Use Modern Sampling Scope



203 sweeps:	average	low	high	sigma
maximum(B)	22.7 W	21.8	23.9	0.4
area(B)	1.95002 µJ	1.80200	2.09265	0.05177
mean(B)	4.86 W	4.49	5.22	0.13

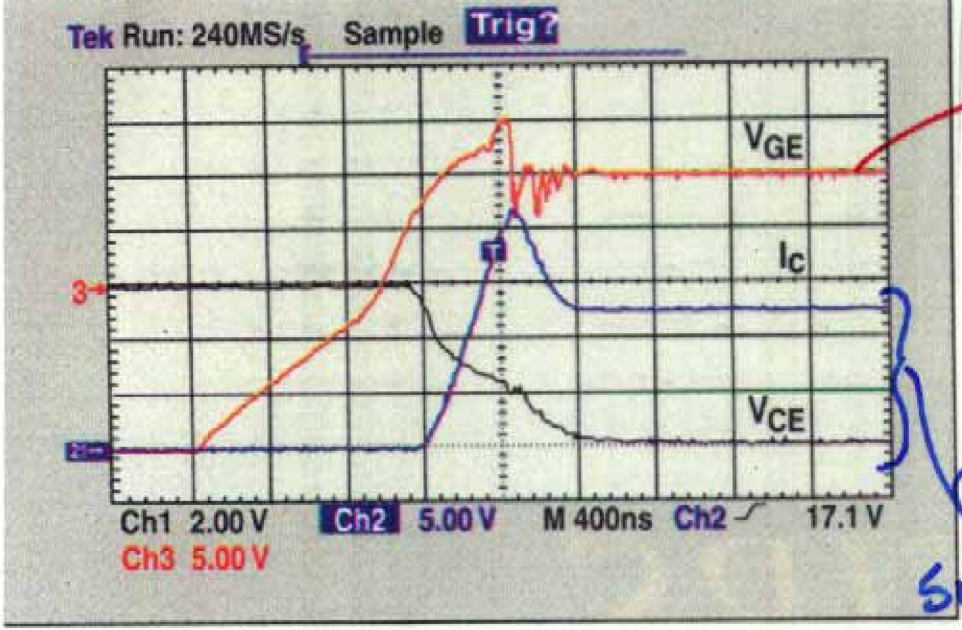
Fig 4b: Turn-Off Loss Calulations

Conclusions: IGBT

6kV

- Becoming the device of choice in 500 to ~~1700~~V+ applications, at power levels of 1-1000kW
- Positive temperature coefficient at high current —easy to parallel and construct modules
- Forward voltage drop: diode in series with on-resistance. 2-4V typical
- Easy to drive —similar to MOSFET
- Slower than MOSFET, but faster than Darlington, GTO, SCR
- Typical switching frequencies: 3-30kHz
- IGBT technology is rapidly advancing:
  - 3300 V devices: HVIGBTs
  - 150 kHz switching frequencies in 600 V devices

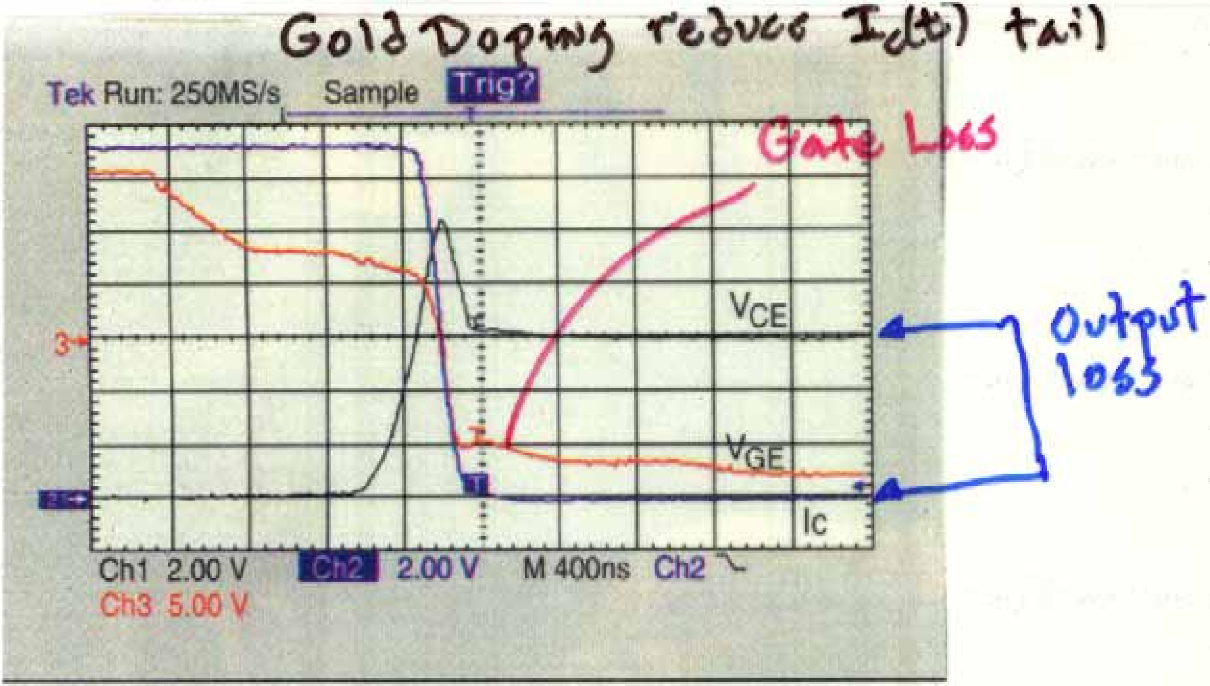
Real Switch Waveforms



① Drive Voltag also has transients and losses not in Erickson

② Output Sw losses

Fig. 4(a). *FS450R12KE3 characteristics: Turn-on.*



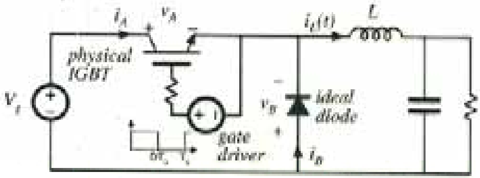
Gold Doping reduce $I_c(t)$ tail)

Gate Loss

Output loss

Fig. 4(b). *FS450R12KE3 characteristics: Turn-off.*

Switching loss due to current-tailing in IGBT



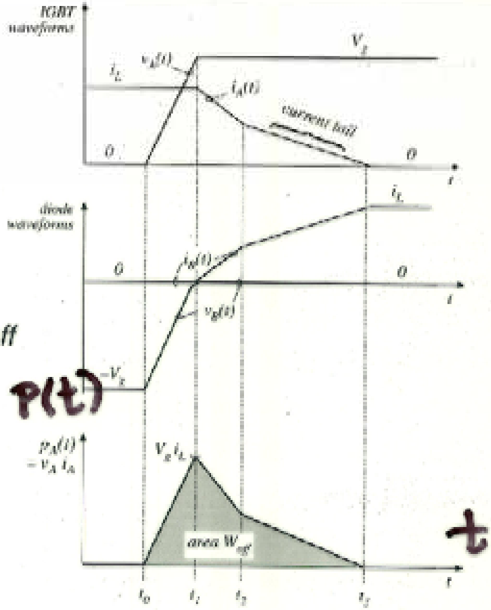
Example: buck converter with IGBT

transistor turn-off transition

f_{sw}

each sw cycle

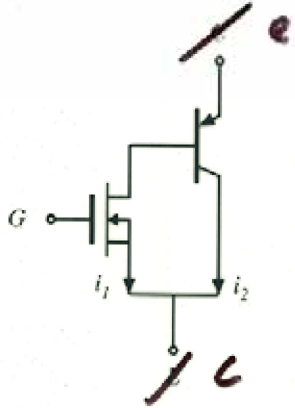
$$P_{sw} = \frac{1}{T} \int_{\substack{\text{switching} \\ \text{transitions}}} p_A(t)\, dt = (W_{on} + W_{off})\, f_s$$

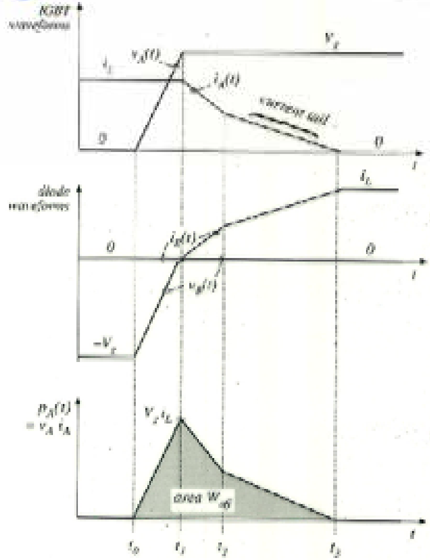


Pb.m 4.7

Current tailing in IGBTs

Causes E_{sw} (off-on)





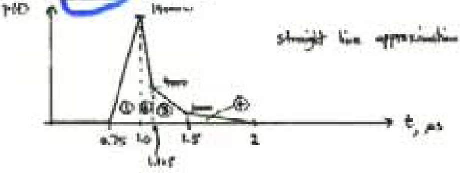
Modern scope → E_{total} for transition

Problem 4.7

Multiply $v_{CE}(t)\, i_C(t) = p(t)$

Estimate energy under $p(t)$ waveform by graphical integration

IGBT turn-on transition



straight line approximation

Sum areas ① – ④:

① $\frac{1}{2}(14000)(0.25 \cdot 10^{-6}) = 1.75\ mJ$

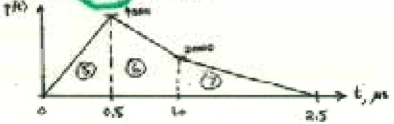
② $\frac{1}{2}(14000+4000)(0.125 \cdot 10^{-6}) = 1.125\ mJ$

③ $\frac{1}{2}(4000+1000)(0.375 \cdot 10^{-6}) = 0.9375\ mJ$

④ $\frac{1}{2}(1000)(0.5 \cdot 10^{-6}) = 0.25\ mJ$

total $4.1\ mJ = E_{on}$

IGBT turn-off transition



⑤ $\frac{1}{2}(4000)(0.5\,\mu s) = 1.0\ mJ$

⑥ $\frac{1}{2}(4000+2000)(0.5\mu) = 1.5\ mJ$

⑦ $\frac{1}{2}(2000)(1.5\mu) = 1.5\ mJ$

total $4.0\ mJ = E_{off}$

each cycle at f_{sw}

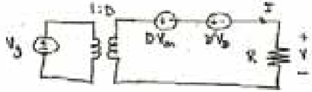
Total $E_{on} + E_{off}$

$E_{sw} = 8.1\ mJ$

(any estimate near this value is OK)

Diode: DC losses Buck are f(D)
b) IGBT

Buck converter model: conduction loss



$V_g = 400$ V
$V = 200$ V
$I = 10$ A
$R = 20\,\Omega$
$V_{on} = 2.5$ V
$V_D = 1.5$ V

$V = DV_g - DV_{on} - D'V_D$

$\Rightarrow V + V_D = D(V_g - V_{on} + V_D)$

so $D = \dfrac{V+V_D}{V_g - V_{on} + V_D} = 0.505$

Element	**power loss**
IGBT	$I\,DV_{on} = 12.6$ W
diode	$I\,D'V_D = 7.4$ W
total	20 W $= P_{cond}$

DC loss both switches

c) Converter efficiency $= \dfrac{P_{out}}{P_{in}}$ with $P_{out} = (200\text{V})(10\text{A}) = 2$ kW

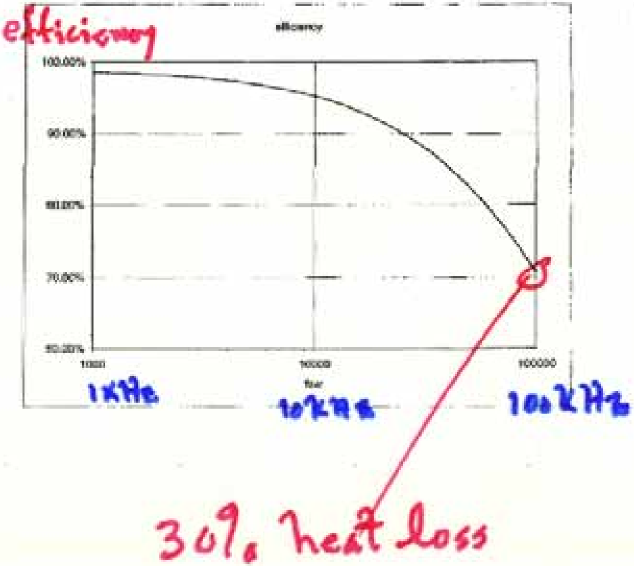
$P_{in} = P_{out} + P_{loss} = P_{out} + P_{cond} + E_{sw}f_{sw}$

$$\text{so}\quad \eta = \frac{P_{out}}{P_{out} + P_{cond} + E_{sw}f_{sw}} = \frac{2000}{2000 + 20 + (8.1\cdot 10^{-3})f_{sw}}$$

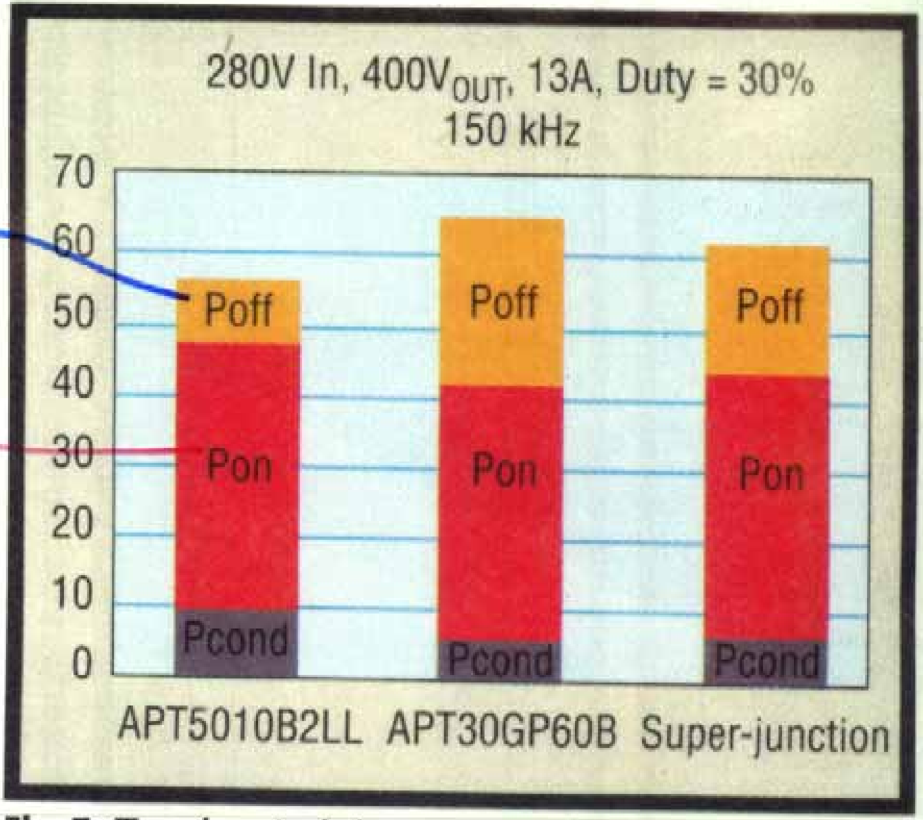
Plot on next page

From Eq. (4.23): $f_{crit} = \dfrac{20\text{W}}{8.1\text{mJ}} = 2.5$ kHz

Problem 4.7, part (c)
Efficiency vs. switching frequency



30% heat loss



P_{off} ↑
due to
slow i(t)
turn off

P_{on}
I_{on} V_{CE}

Fig. 7. *Total switch losses, 13A, 30% duty.*

$R_{DS}(ON)$ Origins in Si Technology

$R_{DS}(ON) \sim$ 10 - 100 mΩ

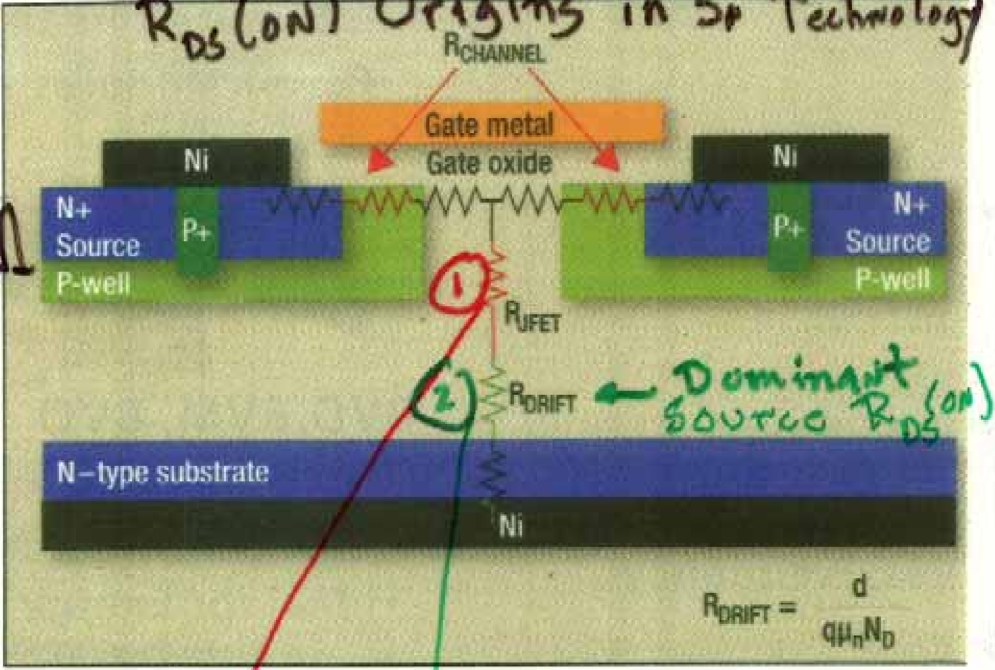


Fig. 1. *Cross-section of DMOSFET power transistor shows i resistive components: the channel resistance, the inheren JFET resistance and the drift resistance that combine to produce a relatively high on-resistance.*

SiC Technology R(drift) ↓
R_{ON} ↓ by *10

SiC $\Delta R_{on}(I)$ $\approx \frac{1}{10} \Delta R_{on}(I)$ for Si

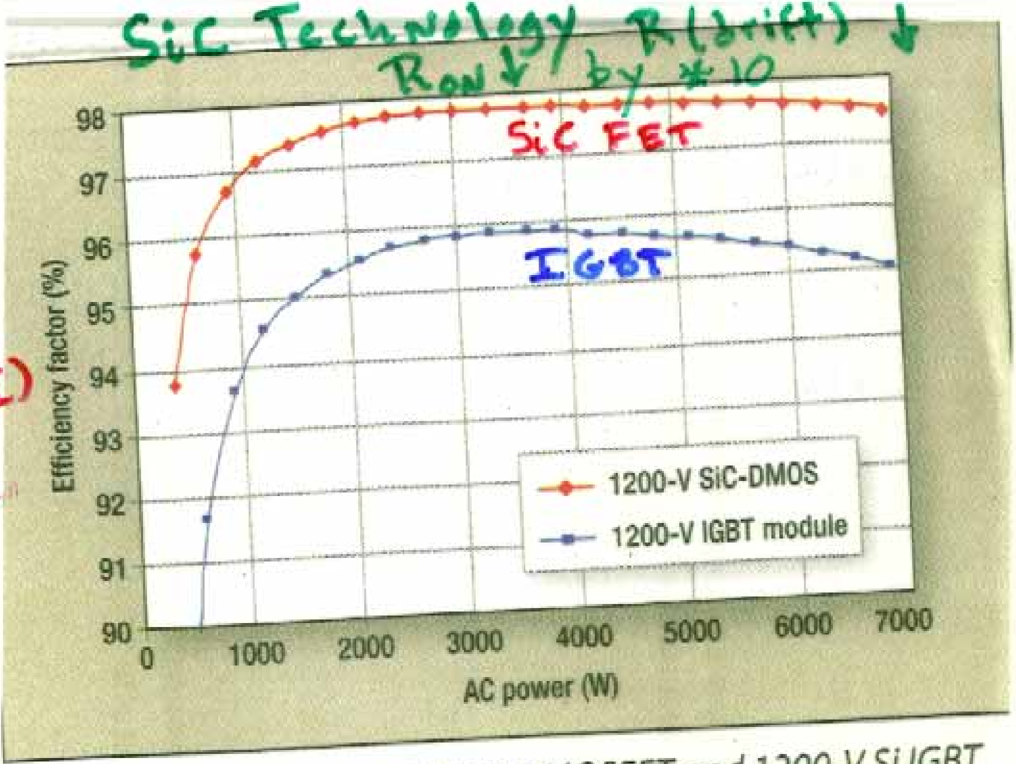
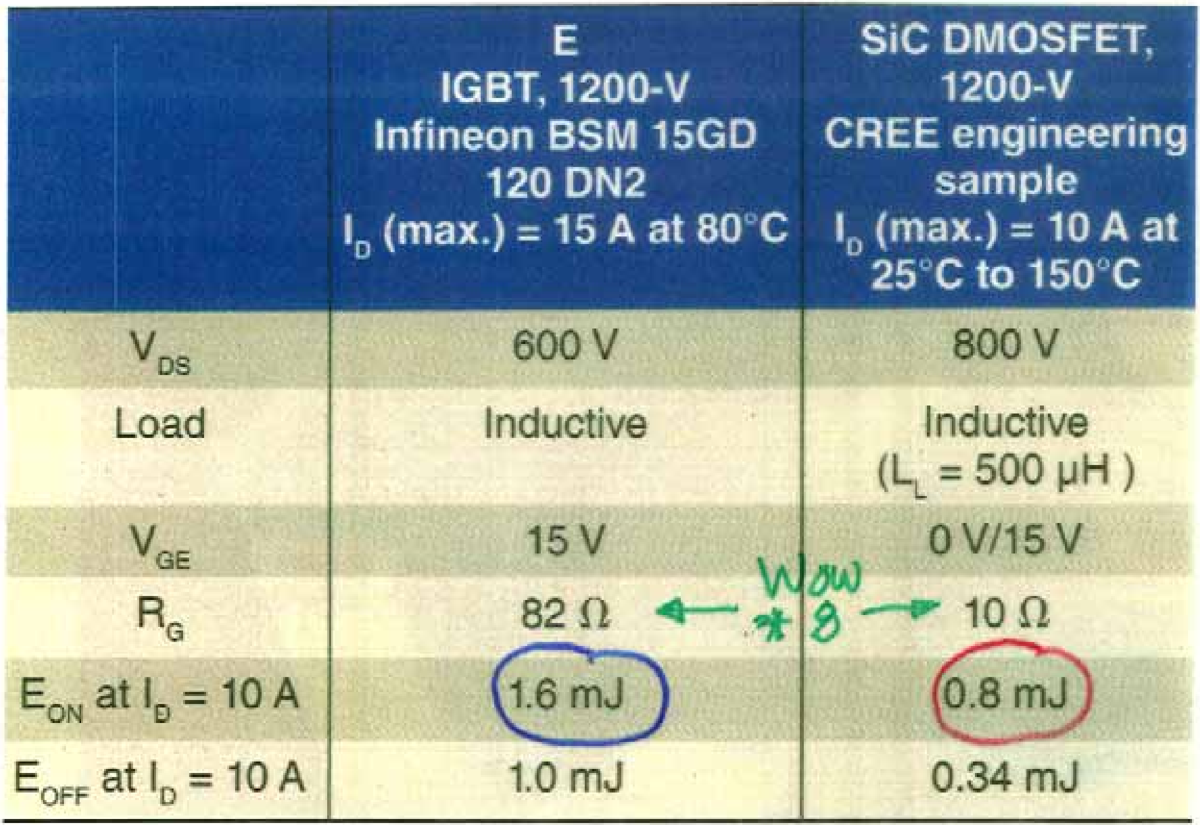


Fig. 2. *Comparison of 1200-V SiC DMOSFET and 1200-V Si IGBT efficiencies in a three-phase inverter shows that at the same voltage rating, the higher-efficiency SiC DMOSFETs provide a* … *their Si IGBT counterparts.*[3]



	E IGBT, 1200-V Infineon BSM 15GD 120 DN2 I_D (max.) = 15 A at 80°C	SiC DMOSFET, 1200-V CREE engineering sample I_D (max.) = 10 A at 25°C to 150°C
V_{DS}	600 V	800 V
Load	Inductive	Inductive (L_L = 500 µH)
V_{GE}	15 V	0 V/15 V
R_G	82 Ω	10 Ω
E_{ON} at I_D = 10 A	1.6 mJ	0.8 mJ
E_{OFF} at I_D = 10 A	1.0 mJ	0.34 mJ

Wow

← *8 →

Table 1 Switching loss comparison [2]

SiC Δt (tail) turn-off ≈ $\frac{1}{2}$ Si Δt (tai)

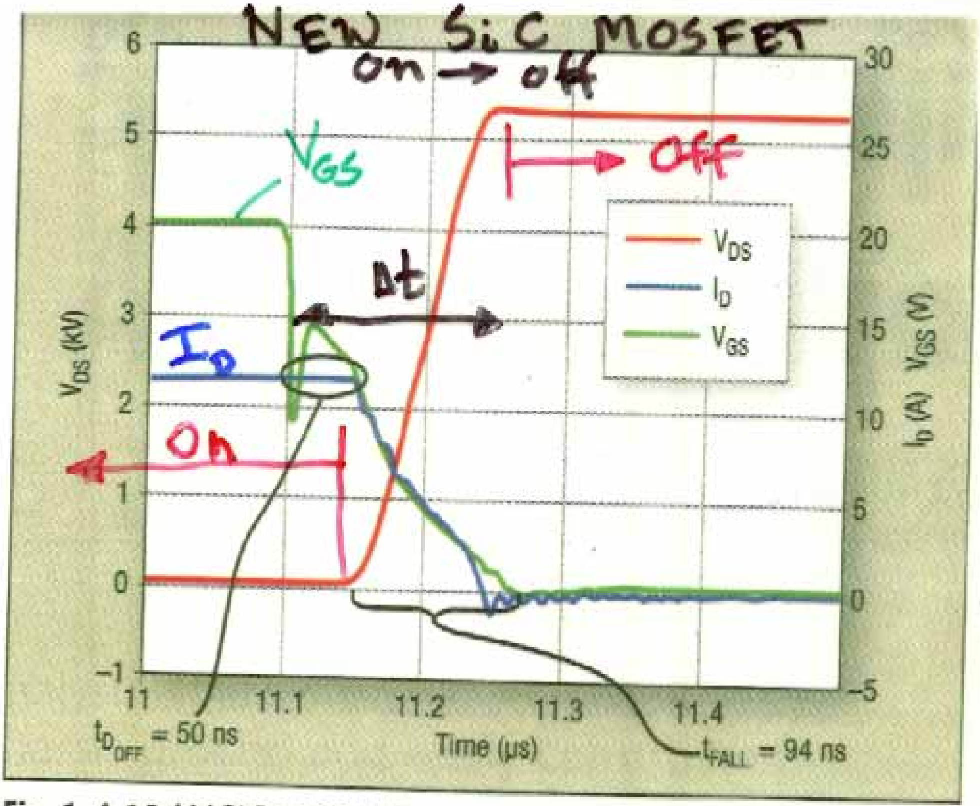
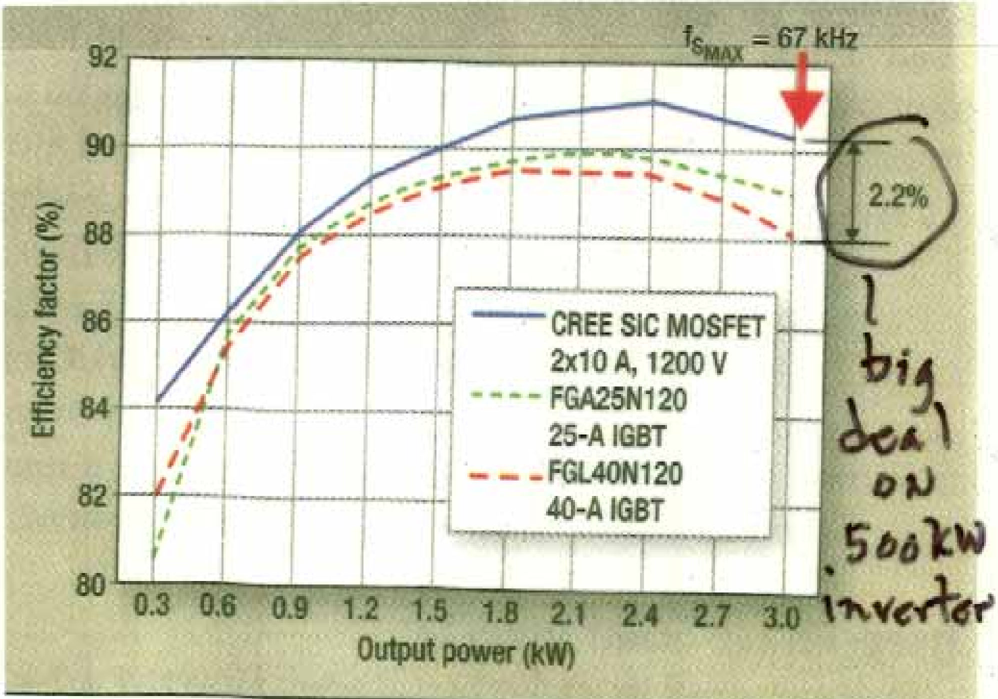


Fig. 6. *A 10-kV SiC MOSFET running at 20 kHz and dissipating 600 W exhibited about 1.5-μs drain current turn-off transient.*[6]



big deal on 500kW inverter

. 4. *Efficiency profile comparison at 67 kHz shows a higher*
efficiency at 3-kW output and throughout the entire
d curve, as well as a case-temperature reduction with the
SFETs relative to the IGBTs [5]

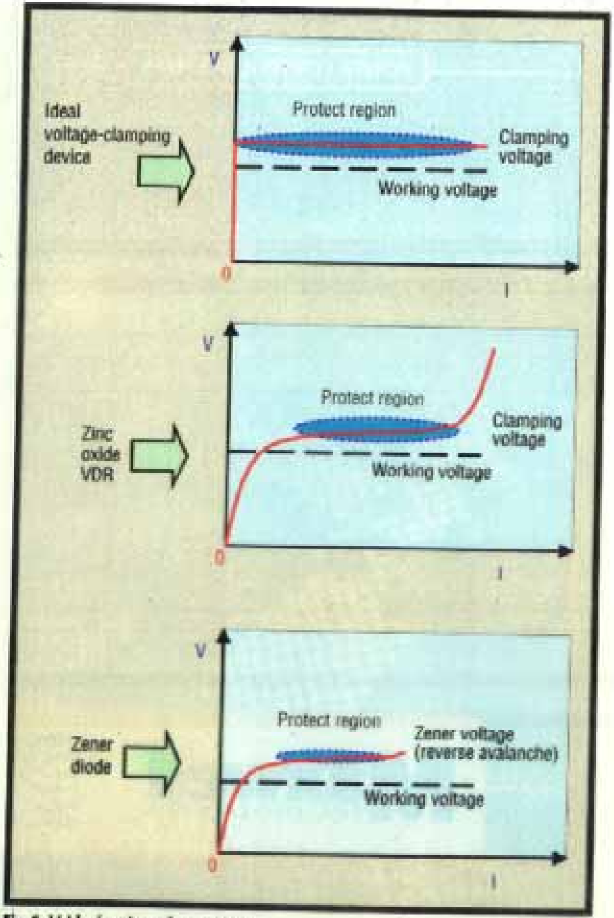


Fig. 1. *V-I behavior of a varistor.*

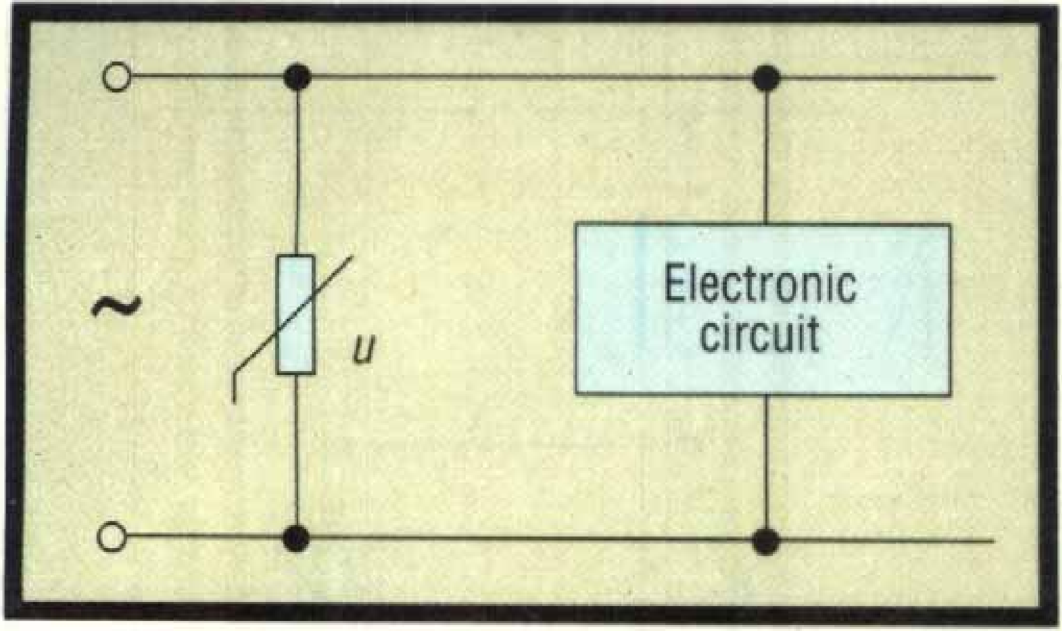


Fig. 4. *Suppression directly across mains.*

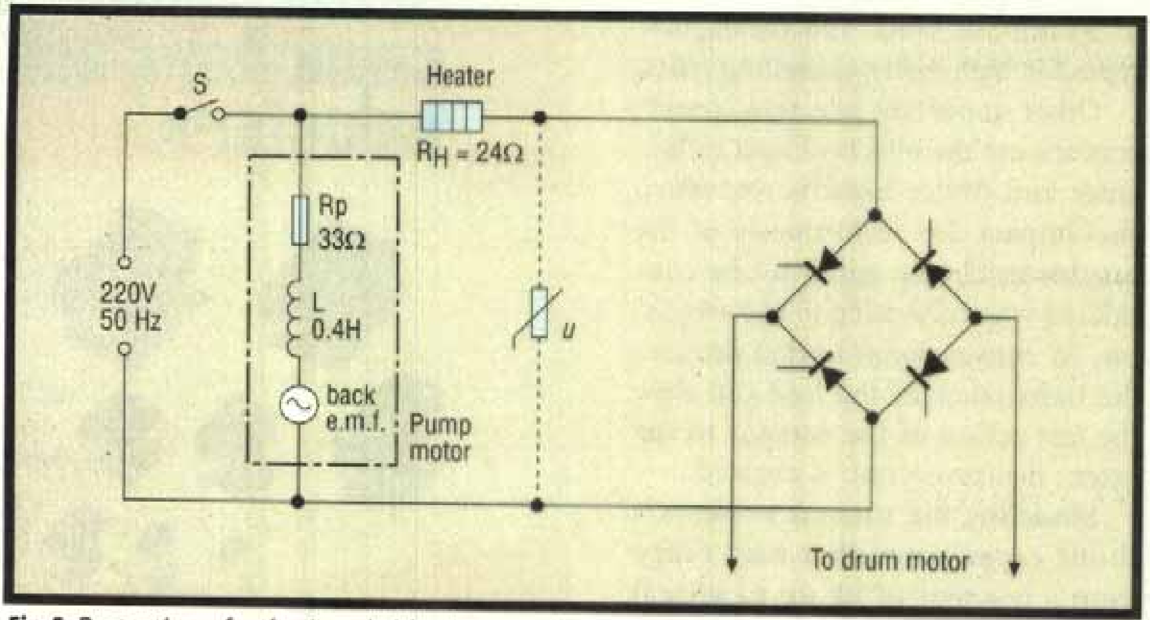


Fig. 5. *Protection of a thyristor bridge in a washing machine.*

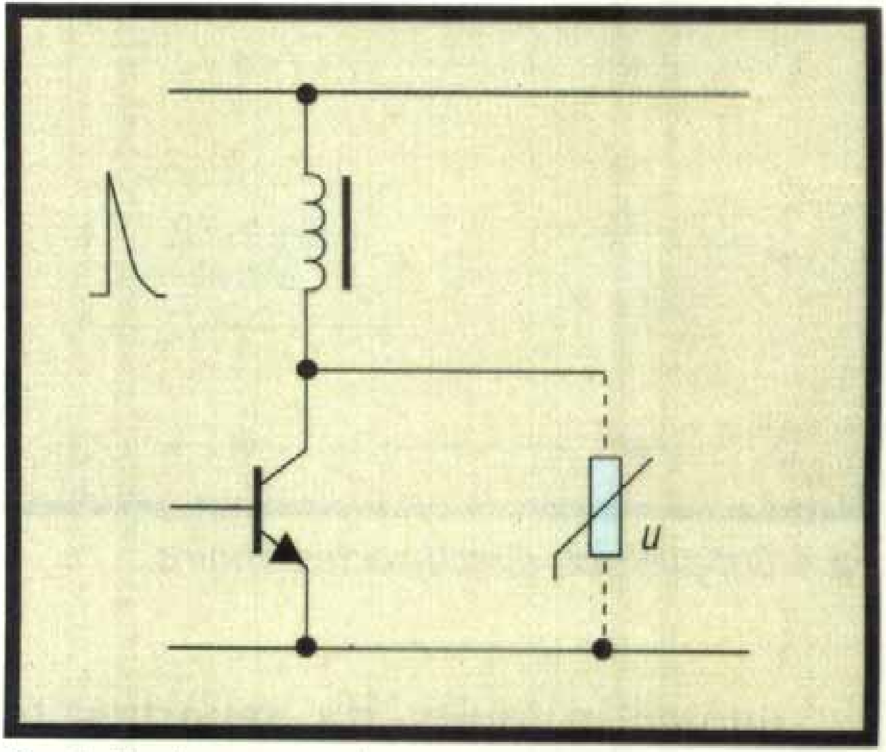


Fig. 6. *Varistors used to suppress internally generated spikes in a TV application.*